The Importance of Monitoring Soft X-ray Sources

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Abstract. The next generation of X-ray monitoring missions should include detectors sensitive to X-rays with energies below 2 keV. This capability will allow us to explore the physics associated with soft sources, including hot white dwarfs, intermediate-mass black holes, soft active galactic nuclei, soft emission in γ-ray burst afterglows, and many X-ray active stars. I also show, using *Chandra* data from 4 galaxies, that more than half of the photons from even so-called “canonical" X-ray sources (with strong emission signatures above 2 keV) have energies below 2 keV. This suggests that soft-X-ray monitoring can open new doors to our understanding of even well-studied sources.

INTRODUCTION

RXTE has made remarkable contributions to our understanding of the physics of X-ray binaries. One area to which it has not contributed, however, is the study of soft X-ray emission (< 2 keV). In this presentation I will argue that there are powerful reasons to design future missions to explore variability in the range $0.1 - 2$ keV.

SUPERSOFT SOURCES

At the time *RXTE* was designed, soft X-ray variability was not considered to be a front-burner issue. By the time the satellite was launched, however, a new class of X-ray sources had been established. Luminous supersoft X-ray sources (SSSs) are characterized by values of kT on the order of tens of eV and by luminosities above roughly 10^{36} erg s^{-1}. SSSs have effective radii comparable to those of white dwarfs (WDs). While some SSSs are known to contain hot WDs, the physical nature of others is still mysterious. Whatever their physical nature, we know that SSSs in our Galaxy are largely obscured from us by the interstellar medium (ISM); it is therefore possible that this poorly understood class is in fact the dominant class of high luminosity X-ray binaries. Di Stefano & Rappaport (1994) estimated, based on *ROSAT* observations and simple models of galaxy absorption, that the Milky Way and M31 may each harbor on the order of 1000 SSSs with $L_X > 10^{37}$ erg s^{-1} and $kT > 30$ eV. There may be ten times as many less luminous SSSs.

Time Variability and the Discovery of SSSs

In our Galaxy we have discovered only a handful of SSSs, and about a dozen in the Magellanic Clouds (MCs). Two lines of evidence suggest that all-sky monitoring could increase by a significant factor the number of known SSSs close enough for detailed multiwavelength follow up. The first line of evidence comes from M31, where we find that a large fraction of SSSs are transient (Di Stefano et al. 2003a). In observations separated from each other by several months, we observe new sets of SSSs, with only a few members in common with SSSs detected during previous observations. This suggests that SSSs are turning off and turning on over time intervals of months. Both because some transients have exhibited on-off-on sequences, and because their number is too large to be consistent with estimated nova rates, most of the transients are likely to be X-ray binaries. Similar systems in our Galaxy and in the MCs must also be transient. In fact, some of the nearby SSS binaries are known to be transient, with pointed observations finding even the flagship source CAL 83, off at least twice during the past 7 years (see Figure 1). The second line of evidence that a large fraction of SSSs are transient comes from the discovery that a nova-like variable of the type VY Scl, V751 Cyg, is a transient SSS (Greiner et al. 1999). Approximately one dozen such sources are close enough to detect should they "turn on" as SSSs.

It therefore is almost certain that the *ROSAT* All-Sky Survey identified only a small fraction of the local SSSs that are actually “on" during a portion of any given decade. Continuous monitoring, spanning a decade, would likely discover several times as many SSSs.

Clues to the Physics of SSSs

Beyond increasing the numbers of SSSs with optical IDs, studying the X-ray variability of each source will provide valuable clues to the physics of those SSSs whose natures are already established and to the natures of those SSSs not yet known to satisfy any specific model.

Models

Known Hot WDs: WD systems known to have exhibited SSS behavior include planetary nebulae (PNe), recent novae, and nova-like variables. In each case, monitoring would allow us to watch the evolution of important features. For example, recent novae can experience an epoch of SSS behavior. Questions yet to be resolved are the time after the explosion when SSS emission, easily obscured by ejecta and winds, becomes detectable, and the duration of the SSS phase.

"Mysterious" SSSs Much of the interest generated by SSSs is due to the fact that the physical nature of a majority of the SSSs with optical IDs is not yet understood. These more mysterious sources include the flagship sources of the class, CAL 83 and CAL 87 (Long, Helfand, & Grabelsky 1981), as well as 7 sources discovered with *ROSAT* (see Greiner 2000 for details). Black hole (BH; Cowley et al. 1990) and accreting-neutron-star models (Kylafis & Xilouris 1993) may apply to some SSSs. Binary models which predict quasi-steady nuclear burning of accreted matter on the surface of a WD are considered promising (see, e.g., van den Heuvel et al. 1992). Nevertheless, studies of external galaxies find evidence that some SSSs may be systems other than WDs. First, we find a significant fraction of SSSs associated with the arms of spiral galaxies (Di Stefano & Kong 2003a, b, c). These may have ages comparable to or smaller than 10^8 years, suggesting donors of higher mass than would be consistent with some accreting WD models. Some SSSs may therefore be NS or even BH binaries. Second, some SSSs are ultraluminous, with $L > 10^{39}$ erg s^{-1} (see, e.g., Kong & Di Stefano 2003). Unless the emission is beamed or the Eddington limit has been circumvented, such systems may be accreting BHs of intermediate mass. Lending credence to this conjecture is the fact that the temperature of the inner disk decreases with increasing BH mass. Thus, if the spectrum includes relatively little hard emission, an intermediate mass BH (IMBH) can appear as an SSS. The soft spectrum should also be characteristic of IMBHs of lower luminosity, implying that a fraction of the many SSSs we detect in external galaxies could be IMBHs.

Monitoring can establish duty cycles, and can determine how long it takes for the soft radiation to turn on and off. It can tell us if some sources that are known to emit hard X-rays at times become SSSs at other times.

Correlations between X-ray and Optical Variations

Another important clue to the physics of a source is the correlation between its X-ray and optical emission. The largest group of relatively nearby SSSs resides in the MCs. Starting during the early 1990's, optical monitoring of the MCs was conducted to search for microlensing events that could signal the presence of dark matter. Some of the SSSs were therefore observed almost nightly. The eclipses of CAL 87, which is viewed nearly edge on were well studied in this way (Alcock et al. 1997). CAL 83 was also monitored. The results are shown in Figure 1; details are available in Greiner & Di Stefano (2002). Note that CAL 83 is highly variable at optical wavelengths, and is transient at X-ray wavelengths. Unfortunately, it is not possible to extract a time history of CAL 83 at X-ray wavelengths from this sparse and irregular sampling, yet CAL 83 is one of the most-studied SSSs. Thus, while there appear to be correlations between the X-ray and optical light curves, better X-ray sampling is needed.

QUASISOFT SOURCES

Searches for SSSs in external galaxies have yielded an unexpected result: the discovery of sources that are somewhat harder than SSSs, but, with little emission above 2 keV, significantly softer than canonical X-ray sources. (See Figure 2.) *Quasisoft* sources (QSSs) have been found in the spiral arms and bulges of spiral galaxies in elliptical galaxies, and in globular clusters. (See Di Stefano & Kong 2003a, b, c, d; Di Stefano et al. 2003a, b; Di Stefano et al. 2004.) Some have been found to be variable on month-to-year time scales; these can potentially be described by WD, NS, or BH models. The existence of QSSs illustrates that even extending the energy sensitivity of an all-sky monitor to roughly 1 keV would allow us to monitor new physical states.

CANONICAL X-RAY SOURCES

It has long been known that some Galactic X-ray binaries, such as Her X-1, have significant soft X-ray components. The effects of absorption, however, have made it difficult to assess the level and significance of soft emission from the large majority of Galactic X-ray sources. For this workshop, I carried out an analysis of the X-ray point sources in 4 galaxies (M101, M51, M83, and NGC 4697), all located along directions with low Galactic absorption. The SSSs and QSSs were identified in previous work, using 3 broad energy bands: $S = 0.1 - 1.1$ keV, $M = 1.1 - 2$ keV, $H = 2 - 7$ keV. (See Di Stefano & Kong 2003a, b, c for the details of source detection and for the method of selecting SSSs and QSSs.)

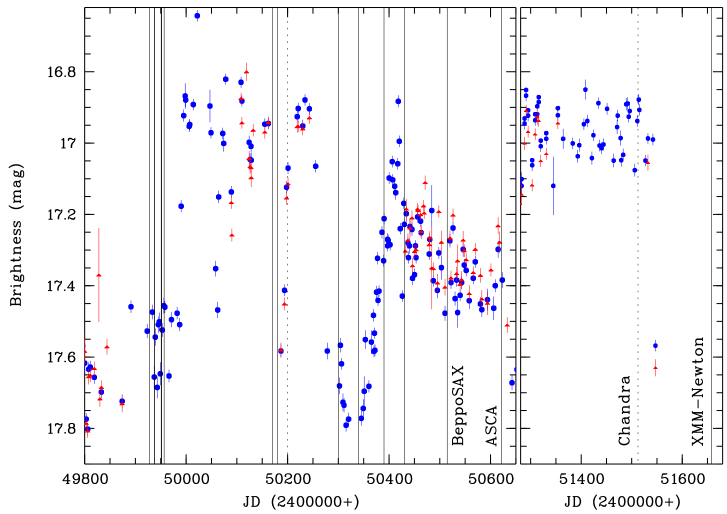

FIGURE 1. MACHO light curve of CAL 83. Blue-filter (V band) observations are marked by filled circles, while red-filter (R) are marked by triangles. Vertical lines denote times of X-ray observations. With the exception of observations with *Beppo*SAX and *Chandra* (individually labeled) all of these have been performed with ROSAT. The full lines indicate normal X-ray "on"-state, while dotted lines mark the two only X-ray "off"-states.

The rightmost column in Figure 2 applies to sources that are neither SSSs nor QSSs; these are the "canonical" X-ray sources. Plotted is the number of canonical sources with a percentage, p, of their emission in the S band (top rightmost panel); M band (middle rightmost panel); H band (bottom rightmost panel). Perhaps the most striking feature of the graph is that no canonical source emits more than 80% of its photons in the hard band, while in most cases, 60% or more of the photons from canonical sources have energies below 2 keV.

Monitoring missions without soft X-ray sensitivity cannot tell us about variability associated with the largest numbers of photons, even for the sources that constitute their primary set of targets. There are no general arguments to rule out soft X-ray variability on time scales of minutes, hours or days. If an all-sky monitor sensitive to soft photons were active, it would almost certainly open up new areas of research for even well-studied X-ray sources.

OTHER SYSTEMS

Distant Systems: Perhaps the strongest argument in favor of soft X-ray monitoring comes from the information it will yield about the distant Universe. X-ray emission from active galactic nuclei (AGN) can be dominated by photons with energies below 2 keV (see, e.g., Grupe & Mathur 2003). Gamma-ray bursts can be followed by X-ray afterglows with a significant and evolving soft X-ray component. The disruption of stars near supermassive BHs by tidal forces is also thought to produce soft-X-ray events (see, e.g., Komossa & Greiner 2000).

Nearby Stars: When searching for SSSs in external galaxies, we consistently find that in most $8' \times 8'$ *Chandra* field covered by the backside illuminated ACIS CCD (the CCD most sensitive to soft radiation), there are roughly $1-3$ foreground stars which are highly variable and which can be distinguished from SSSs only by carrying out correlations with optical data.

PROSPECTS

A short presentation like this cannot do justice to the case for soft X-ray monitoring. In virtually every field of investigation in which X-ray observations are important, soft X-rays are an important component of the X-ray spectrum and are expected to be variable. In addition, there are variable X-ray systems which are active only or primarily at soft X-ray wavelengths. The study of intermediate-mass black holes will, e.g., be hobbled without soft X-ray monitoring. Our understanding of nuclear-burning WDs, possible progenitors of Type Ia SNe, could be significantly improved by soft X-ray monitoring. Certain phases of the X-ray afterglow of γ-ray bursts, soft AGN, and more than 10^5 stars can also be studied with soft X-ray monitoring.

Although soft-X-ray monitoring would be certain to provide important science returns, the prospects for a soft X-ray monitor similar to *RXTE's ASM* are uncertain, largely because the combination of wide-field

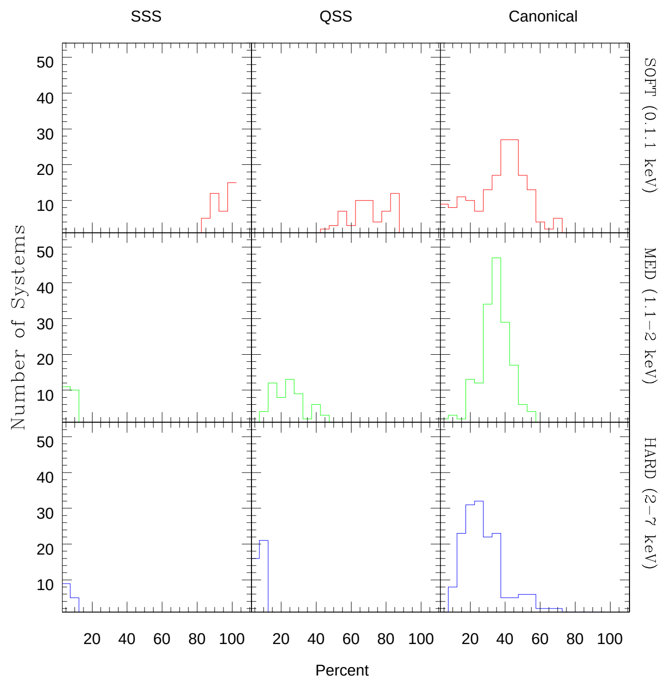

FIGURE 2. The number of systems is plotted versus the percentage of photons with energies in the S band (top panels), M band(middle panels), and H band (bottom panels). The left row shows the results for SSSs, the middle row shows the results for QSSs, and the right row shows the results for canonical (non-SSS and non-QSS) X-ray sources. Note that most canonical X-ray sources emit more than 60% of their photons in the M and/or S bands. *RXTE* is therefore blind to any variations exhibited by the majority of the photons emitted by the sources it observes.

monitoring and soft X-ray sensitivity is technically challenging. Two monitoring projects with detectors sensitive to soft X-rays have been proposed. LOBSTER (http://www.rssd.esa.int/SA-general/Projects/Lobster/) and ROSITA (http://wave.xray.mpe.mpg.de/rosita) would both rely on the *International Space Station (ISS)* to provide a platform. It is therefore not assured that these potentially important science missions will be carried out. Yet, because soft X-ray monitoring can be of critical importance to astronomers interested in the nearby Universe, and in the distant reaches of the Universe, to astronomers interested in the most common of astrophysical systems or the most exotic, designs that seek to achieve soft X-ray monitoring should be central in our discussions of the next generation of monitoring missions.

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